

THE APPLICATION OF MANAGEMENT TECHNIQUES TO WATER RESOURCES DEVELOPMENT AND MANAGEMENT



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**THE APPLICATION OF MANAGEMENT
TECHNIQUES TO WATER RESOURCES
DEVELOPMENT AND MANAGEMENT**

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SUMMARY

Management techniques cover a range of subjects that represent old wine in a new bag, but wine that has been redistilled by the application of electronics, computers and new thinking on goals to be achieved.

Only those techniques have been discussed that have already found application, in 1971, in the work of the United States Bureau of Reclamation or are under consideration for application.

- (1) Tele-measurement of rainfall and streamflow can be used in remote areas, for economizing on manpower, or for up-to-the-minute information as may be, needed for flood control, for instance.
- (2) Computer processing of information can be useful for reasons given under (1) and, in addition, may be necessitated for the handling of many data. The computer programme can be geared to provide various analyses and, where applicable, operational instructions. These instructions can be transmitted and be carried out manually or automatically via the computer.
- (3) Network analysis has been applied to the construction of water works for showing inputs and the timing of activities for reaching given goals. For novel and non-routine activities it is commonly not possible to assess minimum, mean and maximum time requirements for activities in order to arrive at completion of a project by a given date. Such data as to time requirements are needed for formal network analysis. However, for these types of activities, network-type diagrams can still be useful which, like in formal network analysis, show inputs, activities and interrelationships in a time sequence. These diagrams can form the basis for timing analyses when, subsequently, more information on timing becomes available. Several examples of the latter type of presentation are submitted.
- (4) Long-term streamflow records can be analysed for probability of exceedance of a given flow on the basis of which reservoir operation and water-use plans can be drawn up for expectations of probable minimum and maximum flows and for reasonable (mean) flow. This is illustrated for the Granby reservoir in Colorado.
- (5) For important projects the analysis can be extended beyond that discussed under (4) by considering reservoir operation for each flow possibility. This is illustrated for the projected Pa Mong reservoir on the Mekong river on the basis of 40 years of reconstituted flow.

- (6) Studies of the optimization of water resources projects, for minimum cost or maximum benefits, have recently been started, commonly involving the use of dynamic programming. For simple farm problems to which linear relationships apply, linear programming can be used. An example has been given of the graphical solution of such a problem.
- (7) Physical simulation modelling has been widely used in the past. Lately, mathematical simulation modelling has been attempted without recourse to physical models. In spite of results from the latter technique, current aquifer management in Israel remains based on field measurements of the water levels in aquifers in response to withdrawals and recharge.
- (8) An annex is attached listing computer programmes available in the Bureau of Reclamation that have a bearing on operation and maintenance of water resources projects. Other programmes on other aspects of water resources project development and management are available.

INTRODUCTION

Management techniques cover a range of subjects which represent old wine in a new bag, wine that has, however, been redistilled by the application of electronics, computers and new thinking on goals to be achieved.

The general subject has been reviewed by the author while he was attached to the United Nations Economic Commission for Asia and the Far East (ECAFE) with the cooperation from the U.S. Bureau of Reclamation (USBR) and the Drainage and Irrigation Department of the Ministry of Agriculture and Cooperatives, Malaysia. With permission from ECAFE, the original paper has been slightly reworked.

The paper reviews techniques already in use in the USBR (by 1971) or under consideration for application by the Bureau. The review of this large subject is, by necessity, a superficial one that needs to be followed up by treatment in segments alongside consideration of the concept of "river basin development". Suggestions for a possible manner of such treatment have been incorporated in the last paragraph of the Summary.

Management techniques can be reviewed under two headings:

- (a) management techniques employing recently developed techniques in, for instance, aerial photography, laser beams, etc, and automation and computerization of operations; and
- (b) management techniques involving desk work.

Under the first heading, two cases only are referred to in which automation and computerization of the operation of a water project have found practical application.

Techniques under the second heading fall in the domain of operations research, sometimes also referred to as systems analysis, system engineering or decision analysis. They involve the schematization of an undertaking so that the undertaking is expressed as a system or model that can be subjected to analyses. These techniques have recently been applied to public administration, industry, commerce, transportation and other fields (9, 21) but so far there have been few instances of their practical application to water resources projects.

TELE-MEASUREMENT, COMPUTERIZATION AND TELE-OPERATION

Conventionally, measurement of rainfall and streamflow is done manually and observations are transmitted in print, by telephone or radio to a central office for recording, analysis and decision making. However, lately tele-metering is undertaken in a number of places (see, for instance (3)) at given intervals or on call. Usually, the measurement of a water level by a float or an electrical contact provides the basic information. For tele-communication a source of energy needs to be available at the site of measurement. This may consist of a battery or, in cloud-free areas, of a solar cell. A battery can be automatically recharged in a remote area by a thermo-electric generator or an engine-generator set, using e.g., propane gas stored in cylinder. For details of these and other related techniques see reference (15).

Conventionally, recording, compiling and analysis are done by desk work, but the back-log of observations and their significance have increasingly led to automatic data processing (ADP). A computer can be programmed in such a way that the basic data can lead to direct information needed for decision making or the computer can be used to make the decision itself. Conventionally, management decisions are tele-communicated by telephone, radio or in print, but the computer can be used to automatically tele-transmit management decisions it reaches and to implement them. Thus, the setting of a gate opening for water retention or release, or the starting and stopping of a pump can be carried out by a computer. The modern operation of an electric power system, in which thermal and hydro-power are integrated, gives a typical example of these types of operations. Under all circumstances, a selection of the method of data taking, transmission and processing is determined by

- (a) the availability of skilled and reliable personnel;
- (b) the cost of alternative methods; and
- (c) the urgency of decision making.

A number of computer programmes developed by the United States Bureau of Reclamation that have a bearing on the above and other problems in operation and maintenance of water resources projects are listed in Appendix I.

NOTE: Numbers between brackets refer to reference in list at end of paper.

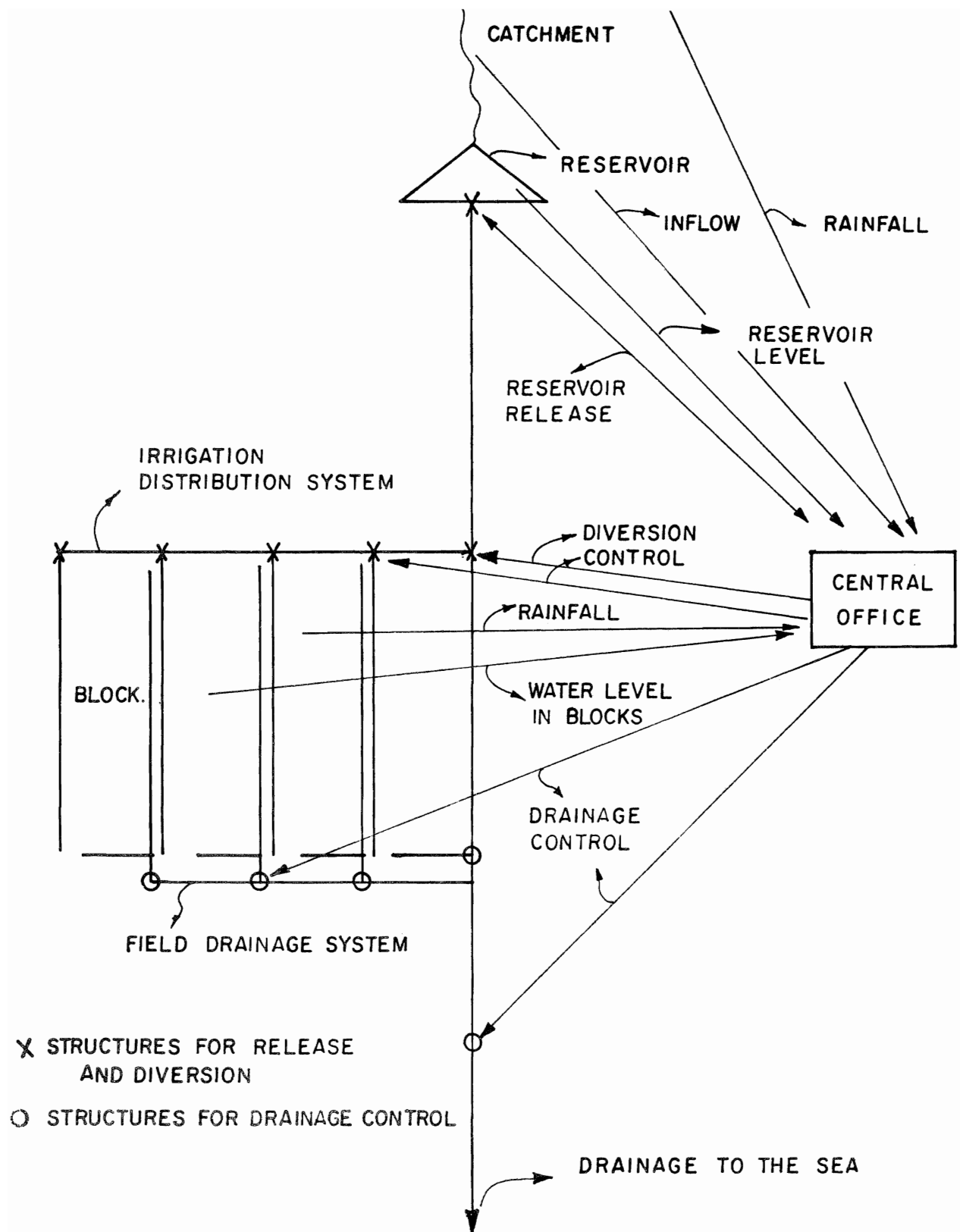


FIG. 1 MODEL OF OPERATION OF MUDA PROJECT, MALAYSIA.

Two examples are given below where tele-measurement and computerization have been applied to the operation of a water resources project.

(1) For the operation of the Muda irrigation project tele-metering is done of rainfall, reservoir inflow and level, reservoir discharge and water level within rice fields. These are tele-transmitted to a central office where decisions are made on reservoir release, diversions to various fields and drainage (Fig. 1). Tele-operation has not yet been applied.

The motive for installing this system resides in:

- (a) making optimal use of restricted reservoir space,
- (b) utilizing the potential field storage within rice fields on a project-wide basis, and
- (c) coordinating the timing of use of limited farm equipment and limited drying and processing facilities.

Reservoir storage was purposely kept limited in that use can be made of field storage within rice fields, rice being grown under partly submerged or waterlogged conditions. The upper limit of this field storage is set by a border-overflow height, reached after heavy rainfall, and the lower limit is determined by an incipient cracking of the surface soil. Within these two limits the one-time potential storage is 12 centimetres depth of water, a storage that is periodically replenished, partially or wholly, by rain. Seasonally, this potential field storage accounts for as much as 1,000 million cubic metres of water, equivalent to one metre depth of water over the project area of 100 000 hectares, a quantity that is roughly equivalent to that retained by reservoir storage.

The utilization of field storage (normally within the root-zone) is, of course, a common practice, but in this case, for operation purposes, storage is considered per block of land of about 100 hectares rather than per individual field or for each crop, as is commonly the case.

Water requirements of rice vary according to the growth stage and by staggering planting, a continuous variation in irrigation and drainage requirements is created in various parts of the project area. The staggering of plantings allows limited water resources, equipment and facilities to be spread, but it also requires day-to-day timing of various activities on parts of the project area, a requirement that had led to computerization of water control and other activities.

It will be noted that the key to this operation lies in the management of farmlands within one block of a given size. Certain implications arise out of this:

- (a) As long as flood irrigation is used, the topography within a given block of land must be conducive towards the application of one given depth of water over the whole surface. (There is some margin for manipulation within a block but this can unduly complicate the system).

- (b) The soil type should be uniform so that there is negligible variation in percolation rate and water-holding capacity.
- (c) Fertility levels should be uniform to avoid uneven growth; and
- (d) One crop of the same variety must be grown all over one block.

It is obvious from this description that this scheme is a novel one and the ultimate results of the 'experiment' cannot be foretold at this time.

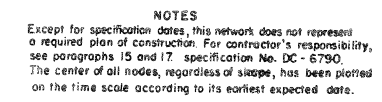
(2) A second example concerns flood forecasting and flood control in Japan. Rivers in that country are characterized by short runs and steep gradients. In the southern half of the country they are subject to intense, wide-spread typhoon rainfalls that can last for several days. This combination of factors tends to create severe flooding in the coastal lowlands. Far-reaching flood-control measures are needed and justified to protect urban areas and industrial complexes near the coast.

Several methods have commonly been applied for flood control, namely:

- (a) man-made river levees or stop banks;
- (b) flood diversion into other rivers, into back swamps, or into special drainage channels running directly to the coast;
- (c) outfall control, particularly through curbing sea-water ingress during high tides;
- (d) river channel improvement; and
- (e) flood-detaining reservoirs.

Of these the first two methods are no longer applicable because of the degree of present-day occupation of the flood plains and the coastal plain. While methods (c) and (d) are applied, major emphasis now falls on the last method, that of detaining flood water upstream in man-made reservoirs.

Flood control for the Yodo river, that flows through Osaka is thus concentrated on flood detention. A weir has been built to regulate the level of Lake Biwa, a major source of the Yodo river, and downstream of it on the mainstream and elsewhere on its tributaries five multi-purpose reservoirs have been built or are in the process of being completed. Three of these reservoirs afford 63 million cubic metres detention of flood water, while Lake Biwa can give 700 million cubic metres flood-water detention per metre depth of storage space. Combined, these afford detention of about half of the major flood discharges.



According to recent reports by the Kinki Regional Construction Bureau of the Japanese Ministry of Construction, optimum regulation is attempted by tele-metering the water level at 25 river stations, 5 reservoir stations and 5 lake stations, tele-metering water discharge at 5 stations, and tele-metering rainfall at 36 stations from a central office, where computers aid in arriving at operation decisions.

NETWORK ANALYSIS

Network analysis has been applied in the past to the construction of water works for improving on the sequencing of inputs and timing of activities in order to arrive at the completion of the project by a given date

Following an assembly of information on needed inputs, on timing of inputs, and on time requirements for activities, a network diagram is prepared showing various inputs (and sometimes also activities) by means of 'nodes' (circles, squares or similar symbols). These commonly represent 'events'. The nodes are linked by arrows representing activities performed with or on the inputs. The diagram from left to right shows the sequence in which the work is to be performed and the timing shown gives the anticipated progress on various dates. Figure 2, the master network prepared for the construction of the third power plant at Grand Coulee dam on the Columbia river (17), gives an example of this type of diagramming.

Dotted arrows in Figure 2 indicate inter-relationships between parallel activities or else show a 'slack', 'float' or 'waiting' period, sometimes referred to as a 'dummy' activity. The dotted portion of an arrow, that is otherwise solid, represents a lapse of time when no immediate follow-up of an activity is necessary or possible; pursuance of the activity must wait the completion of one or more other activities. The length of the arrows shown in Figure 2 represents the time needed for an activity within the time scale shown on the abscissa. In other cases it is not possible to draw a network on a time scale as shown in Figure 2. In that case a master diagram may be drawn on an arbitrary scale and subsidiary diagrams may show the timing more clearly for part of the main activity or of subsidiary activities (2).

Several double lines are shown in Figure 2 that do not include a dotted section. These represent the 'critical path', that is a sequence of activities that determine the minimum time within which a project can be completed. In attempts to shorten the time needed for completion it would be necessary to shorten these lines. In line with this, a shortening of the time needed for activities not lying on the critical path would have little effect on arriving at an earlier completion date.

Network analysis can thus show in a coordinated manner the requirements for materials, equipment and workers at any given stage. While the timing shown in Figure 2 may seem rigid, in actual fact a certain latitude has been taken into account during preparation of the data to be inserted in the diagram. Firstly,

possible delays due to winter weather had been taken into account and, secondly, time margins had been worked out for completion of individual activities. The print-out (17) lists hundreds of activities to which have been assigned:

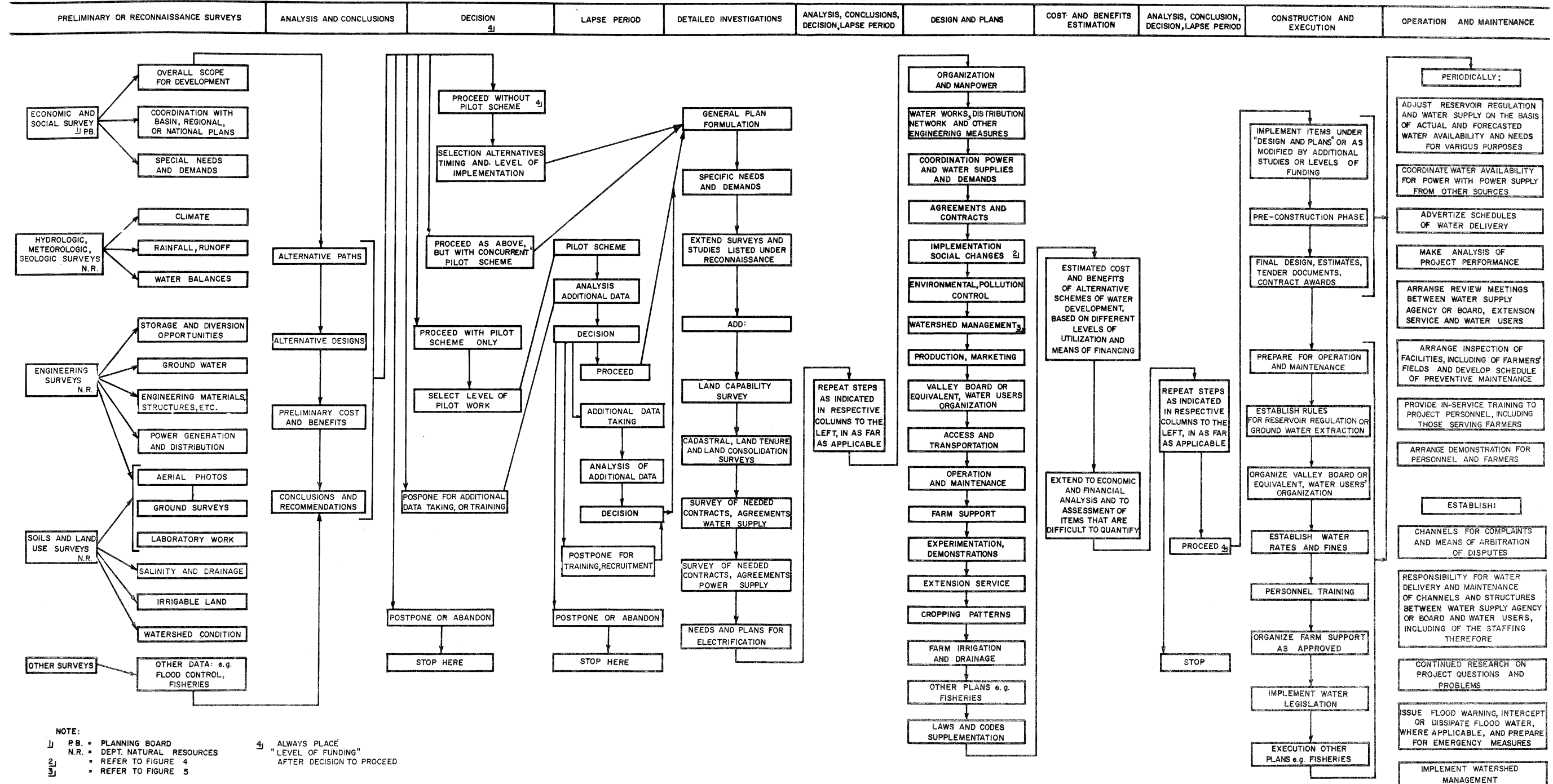
- (a) probable duration of an activity;
- (b) expected date of completion;
- (c) allotted data for completion;
- (d) the slack period; and
- (e) the time remaining for completion of the whole or of part of the project.

The difference between the expected and allotted dates for completion varies from several weeks to months. Non-adherence to the planned schedule, certainly when the activities lie on the critical path, necessitates a rescheduling of subsequent activities. Thus, utilization of the network principle is not a one-time task but a continuing one during the life time of the overall activity. This means that specialists entirely concerned with network analysis only may be attached to a major project and that close team work is needed. Full utilization of the potential of network analysis does involve a lot of work, but experience has already shown that its use can be profitable, particularly for large and complex projects.

Estimation of the duration of an activity at the time background data for the diagram are prepared constitutes a crucial element, requiring knowledge acquired from corresponding activities in the past. Except for certain routine work, such as the pouring of a certain mass of concrete or the hauling of a given volume of earth, no two projects are similar and considerable experience and judgement are needed for arriving at sensible background data. However, once it is possible to establish the information shown under (a) to (e) above, details can be worked out through a computer programme. On the other hand, where such information is not obtainable or has to be established on shaky ground, as applies to non-routine and novel activities, formal network analysis (2) can hardly be applied. This is often pertinent to the overall development of an irrigation project and its subsequent management. Nevertheless, some progress has been made in this direction.

Network analyses have been prepared for the Muda project (Figure 1) which cover the construction as well as the management phases of the project. Thus, networks have been prepared for construction of the reservoir and the reticulation system, for catchment management, for farm localities and farm associations, for the establishment of a credit system, for seeds, fertilizers and pesticides, for publicity, for mechanization, for transportation, for research, for health improvement, for fish stocking, and for social changes. These analyses have provided a better insight into the complexity of developing intensive irrigation farming and have indicated ways and means of handling its multi-faceted preparation.

FIGURE 3 OUTLINE OF STEPS IN WATER RESOURCES DEVELOPMENT AND MANAGEMENT, WITH ELEMENTS OF NETWORK ANALYSIS



When formal network analysis is not possible because of a lack of sound background data (and this often applies to water resources development and management), it can yet be of practical significance to attempt an approach towards this type of analysis by merely enumerating in a diagrammatic form all inputs and activities in a logical sequential manner. This has been attempted for "Outline of steps in water resources development and management" in Figure 3; for "Social changes triggered by water resources development for irrigation" in Figure 4; and for "Watershed Management upstream of an impounded water body" in Figure 5. In preparing these diagrams use has been made of the Muda diagrams and of work earlier done by FAO (7).

Out of these three diagrams, Figure 3 gives an overall review of the subject, but it is not sufficient for detailed planning. Two of many activities shown in Figure 3 have therefore been selected for a further analysis, by way of example, as shown in Figures 4 and 5. Several more diagrams would be needed on specific details for a more complete analysis.

The type of water resources development outlined in Figure 3 would spread over many years, sometimes over as much as 50 years. While at an initial stage the diagram can serve as a checklist, at a later stage when more data become available it may be possible to prepare formal network analysis which, as mentioned, can lead to specific goal setting.

Already Figures 3, 4, and 5 yield information. It is obvious from the information they contain, that operation and maintenance of a project is dependent on preparatory measures which should start with the reconnaissance surveys and on steps that run throughout the sequence of project preparation. A scrutiny of the steps reveals that the leaving out of a step or the missing out on timing of a preparatory measure are likely to result in failure to accomplish the goals of the project as envisaged. While this is known in a general way, the figures pinpoint the steps and this can assist in a more systematic treatment. Even in this form, the figures provide a basis for periodic checks on inputs, activities and performance, for pinpointing delays and weaknesses, and for defining areas where additional work needs to be done.

RESERVOIR OPERATION

Reservoir operation is planned on the basis (a) of direct records on streamflow or (b) of synthesized records. In the first of two examples discussed below, a sufficiently long record (35 years) is available for operational planning and this is subjected to a probability analysis to arrive at mean, extreme low and extreme high inflows. This in turn leads to a planning of water use at these levels of water availability. In the second example reservoir operation is simulated in a much more detailed manner on the basis of 40 years of reconstituted streamflow.

FIGURE 5
WATERSHED MANAGEMENT UPSTREAM OF AN IMPOUNDED WATER BODY; WITH ELEMENTS OF NETWORK ANALYSIS

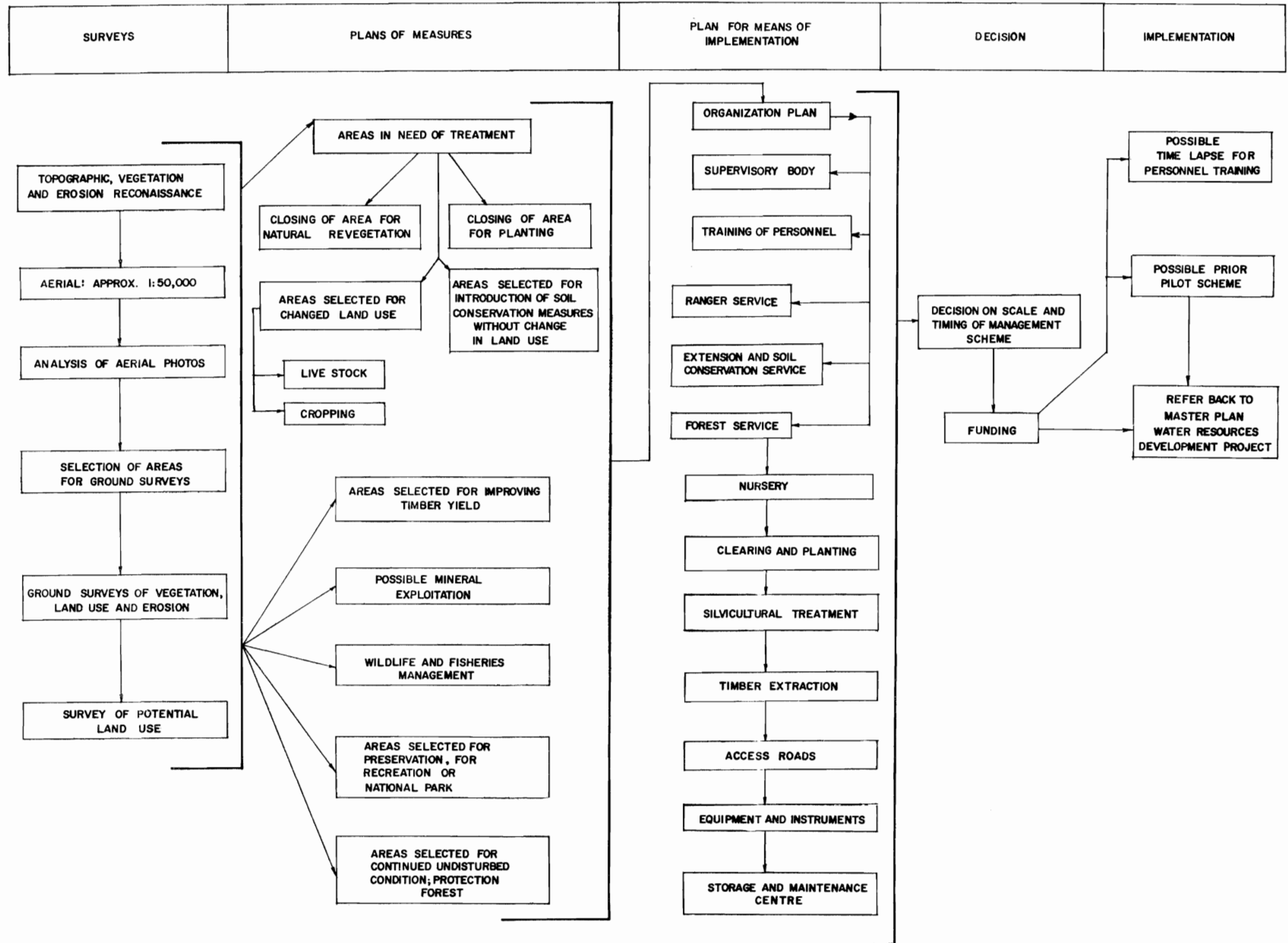
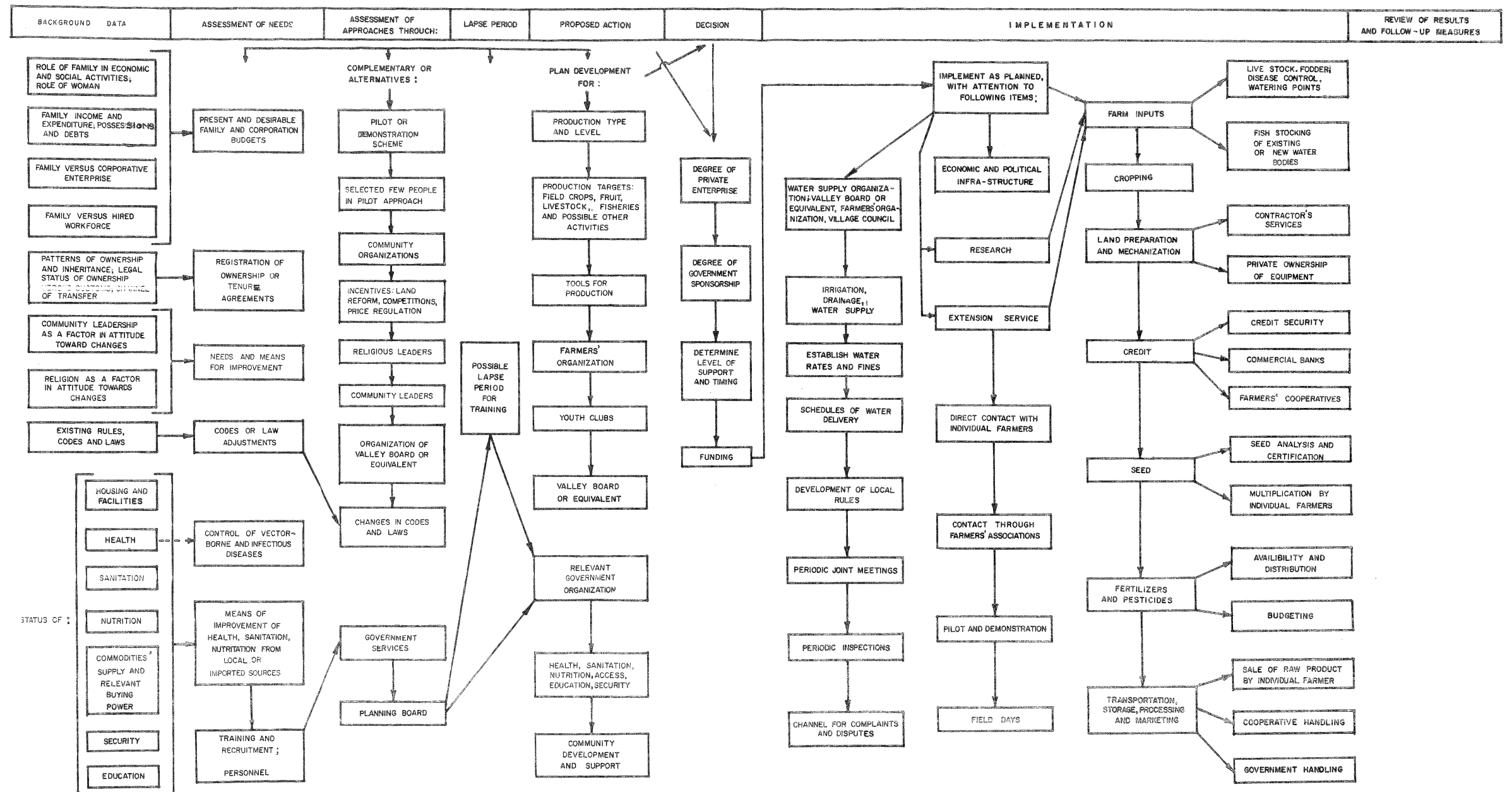


FIG. 4 : SOCIAL CHANGES TRIGGERED BY WATER RESOURCE DEVELOPMENT FOR IRRIGATION, WITH ELEMENTS OF NETWORK ANALYSIS



1. Operational planning using probability of occurrence of three levels of streamflow.

Records of inflow into the Granby reservoir are available over 35 years and are shown in Table 1 (18). These data are analyzed for probability of exceedance (P) by:

$$P\% = \frac{2M - 1}{2N} \times 100 \quad \dots \text{eqn. 1}$$

where M is the relative rank of a particular inflow (M is 1 for the maximum flow and M is N for the minimum flow, see table 1) and N is the total number of observations (in this case N is 35). Three levels are selected for analysis: reasonable maximum and minimum inflow and most probable (mean) inflow, as indicated in Table 1, yielding values of respectively 306,000; 174,000; and 217,000 acre-feet annual inflow with respectively 10, 90 and 50 percent probability of exceedance.

The next problem to be examined is that of seasonal distribution of inflow. During the period March to September, flow into the reservoir is largely a function of snowpack and snowmelt, both of which show substantial variation from year to year. As the demand for irrigation water (a major component in the water use pattern) is virtually confined to these months, March to September are the critical months from a standpoint of operation. During the 35 years of record reasonable maximum and minimum and most probable (mean) inflow during March to September were respectively 288,000; 156,000 and 199,000 acre-feet. On the other hand, during the remaining months, October to February, with no irrigation demand, flow is quite steady and at a low level, averaging 18,000 acre-feet during the whole of the five-months period over the 35 years of record. For the latter months, the average inflow of 18,000 acre-feet was taken to represent the inflow during these months during each of the 35 years. For these months the three probable levels of inflow, are as shown in Table 2.

On the assumption of one or other of the foregoing conditions, operational plans are drawn up for the three sets of conditions for the allocation of water to: firm and secondary power, irrigation, recreation, fisheries, municipal and industrial use, and pollution control, keeping sufficient reservoir reserve space for flood control. By doing so, extremes and average conditions are catered for.

The plans call for secondary power to be reduced or eliminated first during a period of water shortage, so that provisions need be made for substitution by thermal power at that time. At times of extreme water shortage, the allocation of irrigation water is likely to be restricted and farmers must be made aware of this possibility. On the other hand, high inflows

TABLE 1

Probability analysis of annual inflows to Granby reservoir

Water year	Rank (M)	Inflow (1, 000 acre- feet)	Probability of exceedance (percent)	Remarks
1957	1	369.4	1.43	Reasonable maximum range
1962	2	333.4	4.29	
1952	3	321.7	7.14	
1965	4	306.3	10.00	
1938	5	301.7	12.86	
1947	6	293.3	15.71	
1936	7	288.6	18.57	
1949	8	280.4	21.43	
1951	9	262.8	24.29	
1933	10	253.3	27.14	
1960	11	250.7	30.00	
1932	12	241.7	32.86	
1958	13	241.2	35.71	
1945	14	228.6	38.57	
1956	15	225.7	41.43	
1942	16	224.5	44.29	Most probable range
1961	17	223.6	47.14	
1941	18	216.8	50.00	
1935	19	213.1	52.86	
1943	20	211.5	55.71	
1959	21	203.9	58.57	
1939	22	200.8	61.43	
1937	23	196.4	64.29	
1953	24	193.5	67.14	
1964	25	193.3	70.00	
1944	26	185.4	72.86	
1948	27	184.4	75.71	
1940	28	182.8	78.57	
1955	29	180.8	81.43	Reasonable minimum range
1946	30	176.8	84.29	
1963	31	174.2	87.14	
1931	32	173.8	90.00	
1950	33	163.5	92.86	
1954	34	132.0	95.71	
1934	35	117.8	98.57	

TABLE 2

Distribution of monthly inflow to Granby reservoir
for operational planning
(1,000 acre-feet)

	Reasonable minimum inflow		Most probable inflow		Reasonable maximum inflow	
October ^{a/}	5.4)		5.6)*		5.4)	
November	3.8)		3.8)		3.8)	
December	3.3)	18.0	3.3)	18.0	3.3)	18.0
January	3.0)		3.0)		3.0)	
February	2.5)		2.5)		2.5)	
March	3.5)*		2.7)*		3.3)	
April	12.2)		9.4)		16.1)	
May	39.7)		43.3)		64.8)	
June	65.5)	156.0	90.0)	199.0	123.6)	288.0
July	18.6)		33.0)		57.0)	
August	9.3)		10.8)		16.0)	
September	7.2)		9.8)*		7.2)	

^{a/} For the period October - February reasonable minimum, most probable and reasonable maximum inflows are small in relation to inflows for the remainder of the year and for operational purposes are assumed to be the same.

* Apparently these are small errors in the original data. However, they do not interfere with the general conclusions.

lead to the maximum generation of secondary power and, if provisions can be economically made for this, to an increase in the area that can be irrigated. Extremely high inflows, particularly those of short duration are likely to lead to wastage of water to preserve the safety of the dam. The foregoing analysis lays the broad foundation for operation. In addition to the broad plans, annual operating plans are prepared, taking into account such items as initial reservoir content and specific irrigation requirements. Moreover, a day-to-day operational plan is worked out at a central office on the basis of current observations of and forecasts of snowpack, snowmelt and precipitation. The particular office handles a number of projects, making it possible to coordinate water allocations in one river basin with those in another, particularly with regard to power supply and in one case in respect to possible trans-basin water transfer. Several computer programmes are used in these operations (13, 14).

2. Detailed simulated reservoir operation

Often, a length of streamflow record of 35 years (as in the preceding example) is not available and this applied to the site of the planned Pa Mong reservoir on the Mekong river. A few years of records only were available at this site so that some means had to be found for extending the streamflow record for design and operational planning. This was done by reconstitution, that is by establishing correlations between various measuring stations on the river and then extra- or intrapolating the information to the site of the planned reservoir. In this way a record was created for streamflow from 1930 to 1969, a record that was assumed to represent what could happen in the future. A reservoir operation plan was then developed for each month of the 40 years of record, that is for 480 months. In current terminology this can thus be called simulated reservoir operation on the basis of reconstituted streamflow data.

Basic water needs were subsequently established, that is water allocations to irrigation and to industry and domestic use. Water available within the reservoir during or after a period of minimum inflow was then allocated to firm power. Any water available above that of this minimum level was then allocated to secondary power up to the limit of safe reservoir operation. Inflow above the latter level of operation was scheduled for retention within the reservoir for flood control or was scheduled for release as wastage. An estimate of needed flood-water release was based on a study of flood damage by a given flow against cost of flood detention or alternative downstream flood-control measures (11, 12).

The latter study was supported by a separate one on a possible maximum flood once in 200 years, a somewhat arbitrary period often assumed for large reservoirs. The estimate was largely based on the weighting of several physical factors with some extrapolation of available records (20) which constituted a

rather novel approach to the subject, a further discussion of which falls beyond the scope of this paper. The maximum flood inflow thus estimated was $28,000 \text{ m}^3/\text{s}$, the damage-acceptable flood was estimated at $17,000 \text{ m}^3/\text{s}$, requiring a maximum flood-water detention of $11,000 \text{ m}^3/\text{s}$.

The above description, as well as a review of the water allocations during the 480 months of simulation, may give the appearance that this type of exercise is within common reach. However, as explained in reference (10), results are in reality based on many trial and error calculations which could hardly be made for a project of any reasonable size without the use of a computer. As such this type of operational planning has only recently become possible.

In order to aid day-to-day operations, the monthly data were worked up to provide a rule curve, shown in Figure 7, with an indication of critical reservoir levels of importance for its operation in Figure 6. It is seen from Figure 7 that the rule curve, in the usual way, can guide decisions on releases for secondary power and flood control. The implications of the worked out operating programme are further illustrated by an insertion of information on scheduled reservoir operation during a dry year (1959) and a wet year (1965) for which the reservoir level curves can be compared with the 'normal' or 'average' operation indicated by the rule curve in Figure 7.

During the year of low inflow, 1959, at the beginning of June the reservoir level has dropped to 221 metres compared with 236 metres for 'normal' operation. From January to June the gap or space on the graph between the 'normal' (or rule) curve and the actual operating curve shows that no secondary power can be generated. From July to December, inflow brings the reservoir level close to the 'normal' level, but inflow is still at too low a level for secondary power to be produced as shown by the figures for energy production at the bottom of Figure 7.

On the other hand, during the wet year, 1966, Figure 7 shows the initial reservoir level to be above 'normal'. Water releases for secondary power are possible throughout the year as guided by the rule curve which shows the desired reservoir level at any time for satisfaction of basic demand during the first half of the year and largely, for flood control during the second half of the year. The reservoir space for flood control is completely utilized during the latter half of the year.

The data presented do not represent new concepts; they are intended to show refinements in reservoir operational planning made possible by the use of computer calculations.

Lately, several simulation models have been developed of runoff-rainfall relationships and additional statistical techniques and stochastic techniques have been developed for analysing further rainfall and streamflow data. To date, none of the results from these techniques have found acceptance in the development

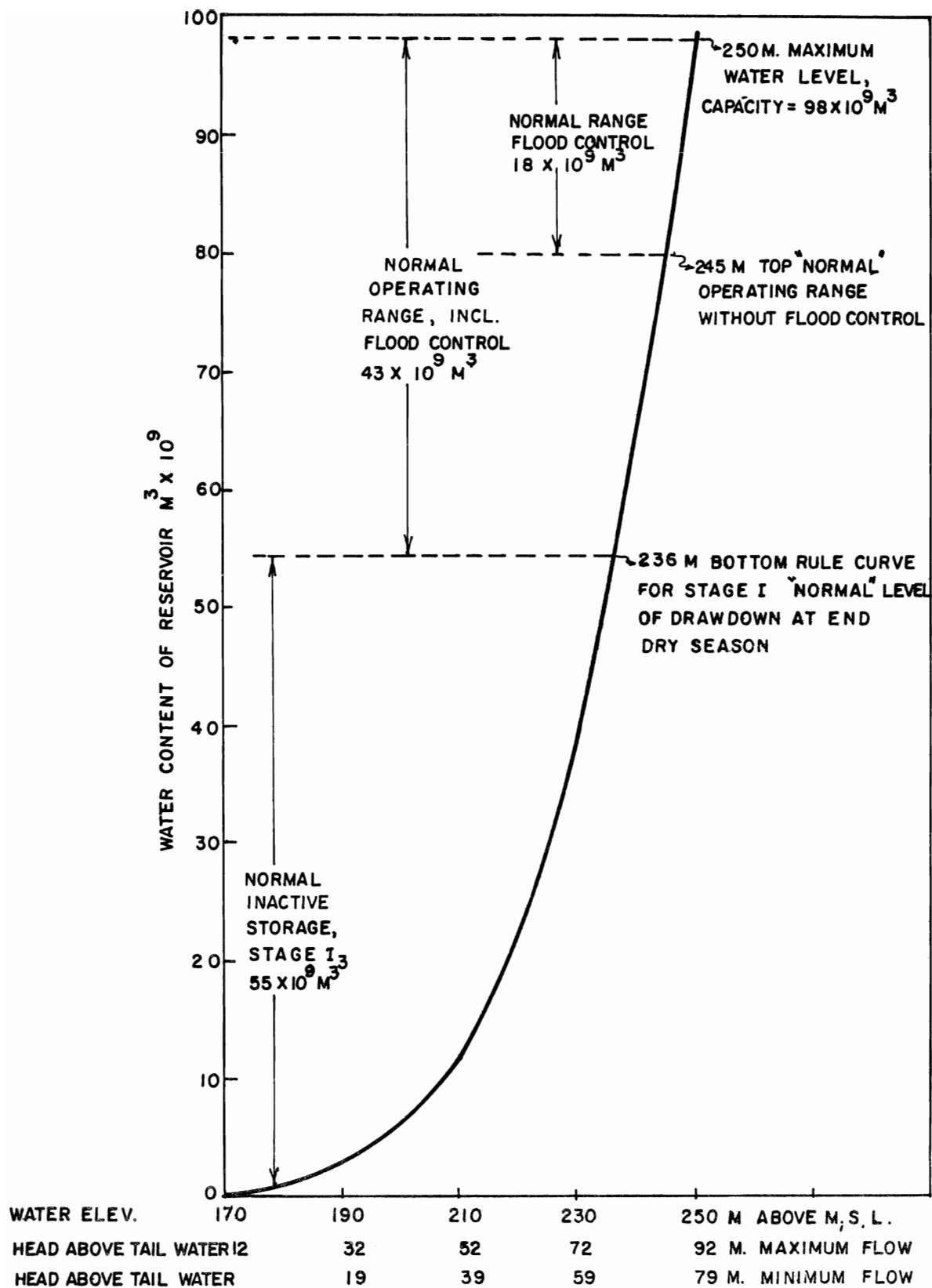


FIG. 6 : PROJECTED CAPACITY OF PA MONG RESERVOIR AT VARIOUS WATER ELEVATIONS, WITH INDICATION OF CRITICAL LEVELS SELECTED FOR STAGE I OPERATION

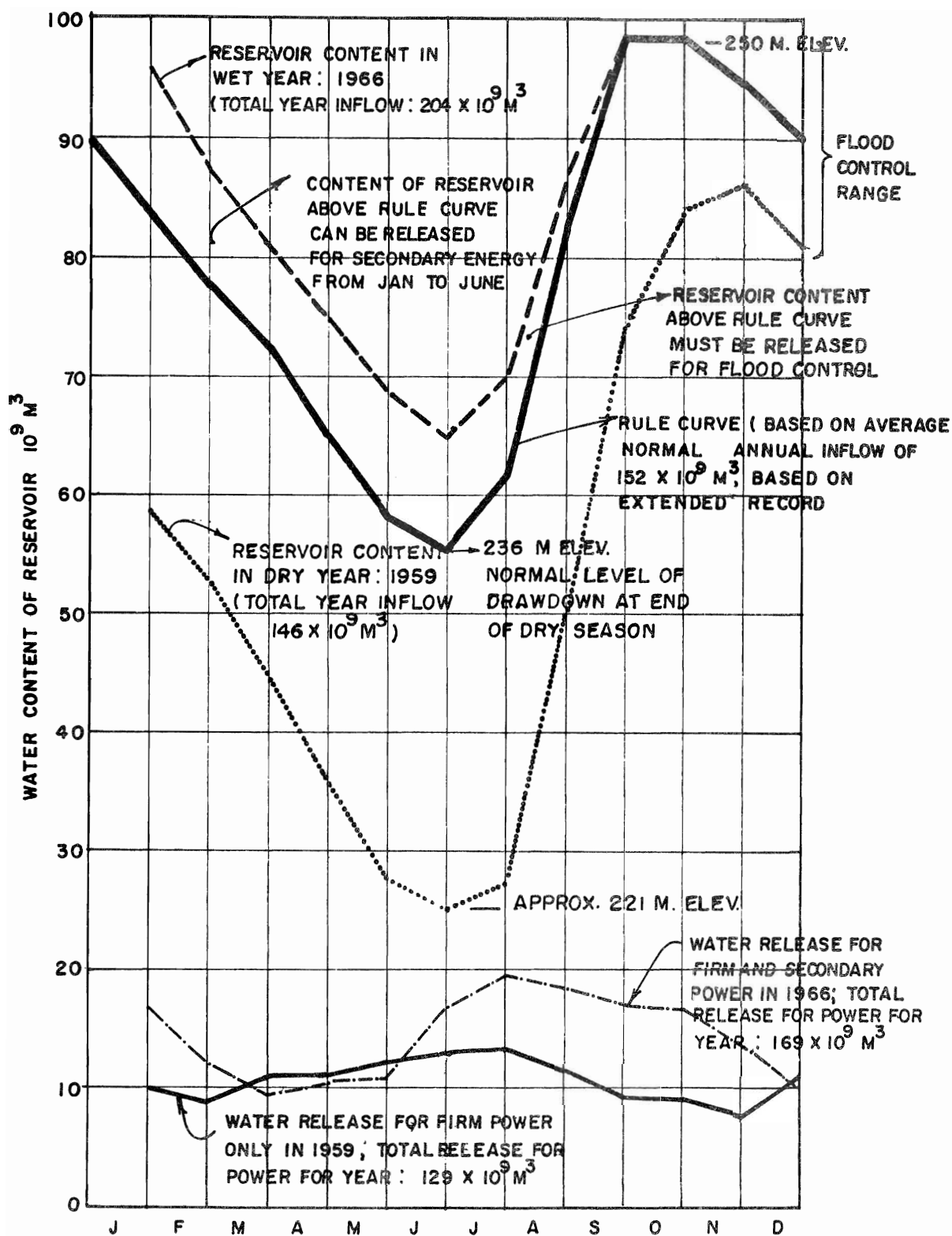


FIG. 7 SIMULATED OPERATION OF THE PA MONG RESERVOIR BASED ON AN EXTENDED RECORD OF STREAMFLOW, SHOWING :

- (1) NORMAL OPERATION FOR AVERAGE ANNUAL INFLOW BY MEANS OF A RULE CURVE;
- (2) ACTUAL OPERATION DURING A WET AND A DRY YEAR; AND
- (3) CORRESPONDING POWER PRODUCTION DURING THE WET AND THE DRY YEAR

of the Mekong project, or elsewhere in the work of the Bureau of Reclamation, or seemingly in any other area where hydrologic data are needed for design and operational planning. A discussion of the reasons for this falls beyond the scope of this paper. Nevertheless, it is possible, even likely, that the newer techniques will provide an additional tool for providing additional hydrologic data, additional to those now available from direct records, from reconstitution and transposition of streamflow data, and sometimes, rainfall data.

SYSTEMS OPTIMIZATION

Any activity, even the simplest, can be viewed as a system for which a model can be prepared. Moreover, any activity can be expressed mathematically in terms of an equation of equality or functional equation. The equation or set of equations describing the activity represents a model of the system. An equation for a chemical reaction shows exactly what is happening. In a more complicated system, such as the operation of a water resources project, some of the components may not be known; estimated or simulated values are inserted instead and subjected to manipulation for optimization. This last statement may be made clearer by reference to a specific case.

Suppose it is desired to maximize the benefits (or minimize the costs) from operating a reservoir. The net benefit (the objective function) is dependent on manageable conditions such as reservoir level that can be varied within certain limitations or constraints. These constraints consist of, among others, the height of the dam, reservoir inflow, available head, and the installed or effective power generating capacity. The net benefit may be a function (f) of: (a) returns from irrigation, (b) power or fisheries, employment opportunities, or (c) indirect benefits from recreation. The maximum net benefit (NB_{\max}) is then expressed as follows:

$$NB_{\max} = f(\text{irrigation, power, fisheries, employment, recreation}) \quad \dots \text{eqn. 2}$$

For optimization one needs to know how much water should be kept in storage and how much released and allocated to each function (the decision variable). For a solution of this equation the components need to be expressed in the same units, say dollars. To enable this to be done it is necessary to quantify the benefits from employment and recreation in terms of dollars and it is here that difficulties in optimization arise.

Assume that it is possible to arrive at a quantified optimization equation. This should lead to a determination of the maximum benefit over a range of reservoir levels for reservoir releases for specific purposes at specific times. A basic expression is:

$$\sum_{t=1}^T = \frac{B_t(y_t) - O_t(x_t)}{(1+r)^t} = C(x) \quad \dots \text{eqn. 3}$$

where

$\sum_{t=1}^T$ = summation of results at time t within the time system T, where $T = t_1 + t_2 + \dots + t_n$; t can be one day, one month, etc;

B_t = gross benefit at time t. The summation would give $B_{t_1} + B_{t_2} + \dots + B_{t_n} = B_t$;

(y_t) = output of system (x). This will depend, for instance, upon reservoir inflow and reservoir level at time t;

O_t = the direct cost of obtaining B_t at time t. Summation of this and the previous terms will be as indicated before;

(x_t) = the system at time t. Summation would apply to $x_{t_1}, x_{t_2}, \dots, x_{t_n} = x_t$. In a reservoir the state of the system would be different for each x_t ;

r = the discount rate; and

C = the amortized cost of the project at time t to be summated during time T.

Instead of an expression that gives total benefits by summation of individual benefits at time t_1, t_2, \dots, t_n within the period T, benefits during time T can be kept constant and the equation solved for the optimization of benefit (B) derived from individual benefits b_1, b_2, \dots, b_n . Other optimization expressions can be developed. Each case requires a study of the relationship existing between the variables and of the feasibility of computation.

In the simplest case, a solution for this type of expression is obtained by setting the derivative at zero, thus deriving a maximum for benefit or a minimum for cost. Most practical problems are too complex for such a simple solution. For two-dimensional linear problems such as the farm problem discussed below, a linear programme solvable by graphical means can be set up. For multi-dimensional linear programmes of higher order, a graphical solution is no longer possible and optimization may be obtainable by application of the Simplex method or another matrix approach.

Many water problems are non-linear but sometimes non-linear functions can be optimized by dividing a non-linear curve in approximating linear segments. Mostly, however, non-linear or dynamic programming is applied. Dracup et al (4) lists twelve search techniques under these headings. While linear

programming has been applied to some practical design problems (13) and to some theoretical analyses (6), neither linear nor dynamic programming seems to have been applied to the practice of operation and maintenance of a water resources project (16). Work on possible application of decision theory, queueing theory and stochastic theory seems at the same level of development.

The following example shows how a two-dimensional problem commonly met at the farm level can be solved graphically in linear programming.

Assume a choice must be made between the growing of two crops, sugar-cane (S) and cotton (C) for which inputs are:

- (i) land area available - 150 acres
- (ii) total water available - 400 acre-feet

	<u>Sugar</u>	<u>Cotton</u>
(a) water required (acre-feet/ton)	0.4	1.6
(b) gross return (\$/ton)	15	45
(c) cost of production (\$/ton)	5	15
(d) yield (acre/ton)	0.2	0.4

The question is: how much of each crop (the decision variables) should be grown for maximum profit, P? This is expressed by the objective function

$$P_{\max} = (15 - 5)S + (45 - 15)C \quad \dots \text{eqn. 4}$$

subject to the constraints of area and water availability, namely,

$$0.2S + 0.4C = 150 \quad \dots \text{eqn. 5}$$

$$0.4S + 1.6C = 400 \quad \dots \text{eqn. 6}$$

The limits of feasibility are graphed in Figure 8. Line A is based on equation 5 which gives a maximum of 750 tons of sugar and 375 tons of cotton. Line B is based on equation 6 which gives a maximum of 1,000 tons of sugar and 250 tons of cotton. These lines define the feasibility space and within this space the optimum point is defined by the intersection of the two lines which gives 500 tons of sugar and 125 tons of cotton. These quantities give the maximum profit (\$8,750).

A check on the validity of this conclusion is as follows:

Profit:	500 tons sugar at \$10/ton	=	\$5,000	(profit based on:
				(b) - (c) above)
	125 tons cotton at \$30/ton	=	<u>\$3,750</u>	
	total profit		\$8,750	

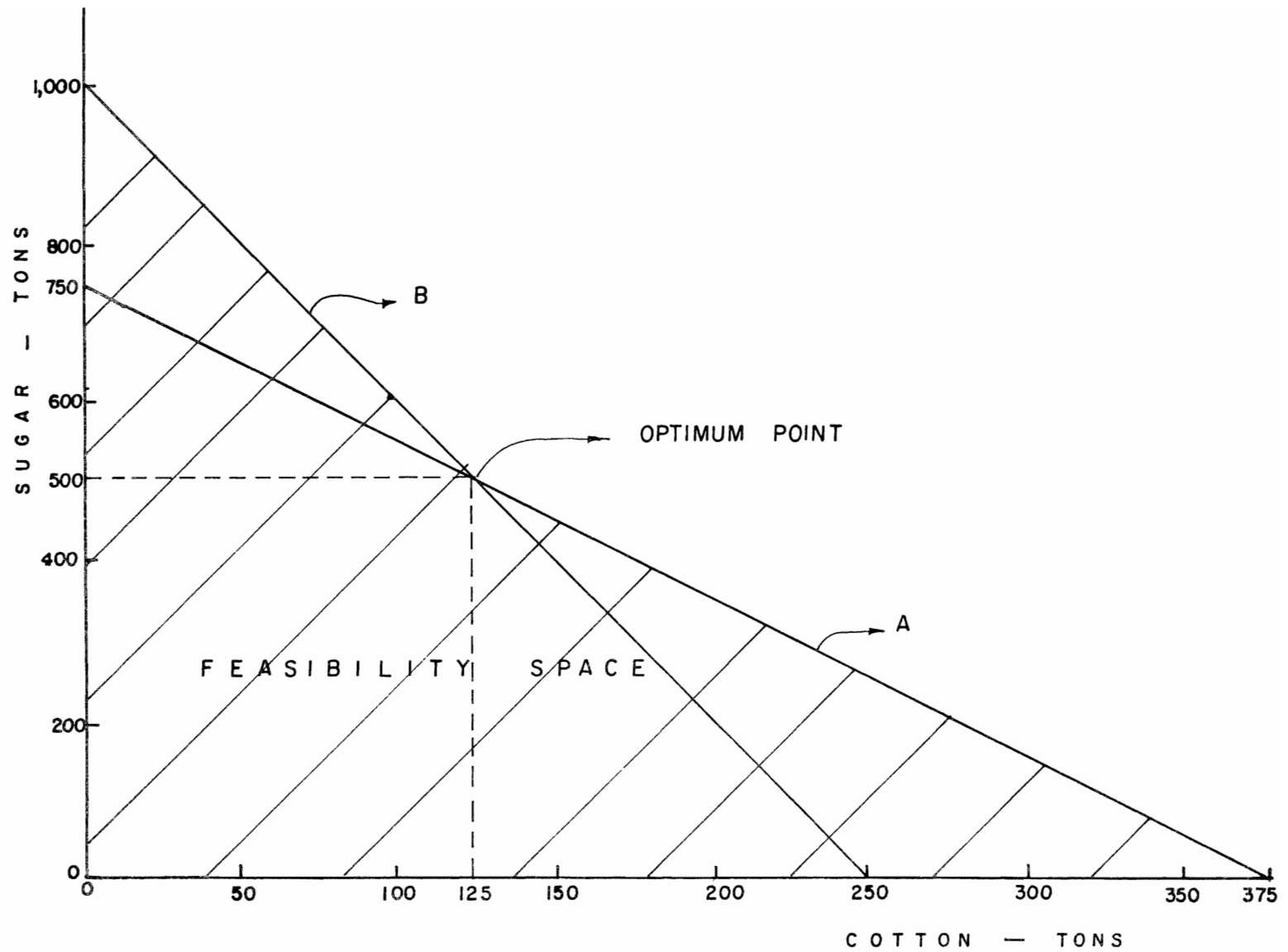


FIG. 8 : GRAPHICAL SOLUTION OF A LINEAR SYSTEM (SEE TEXT)

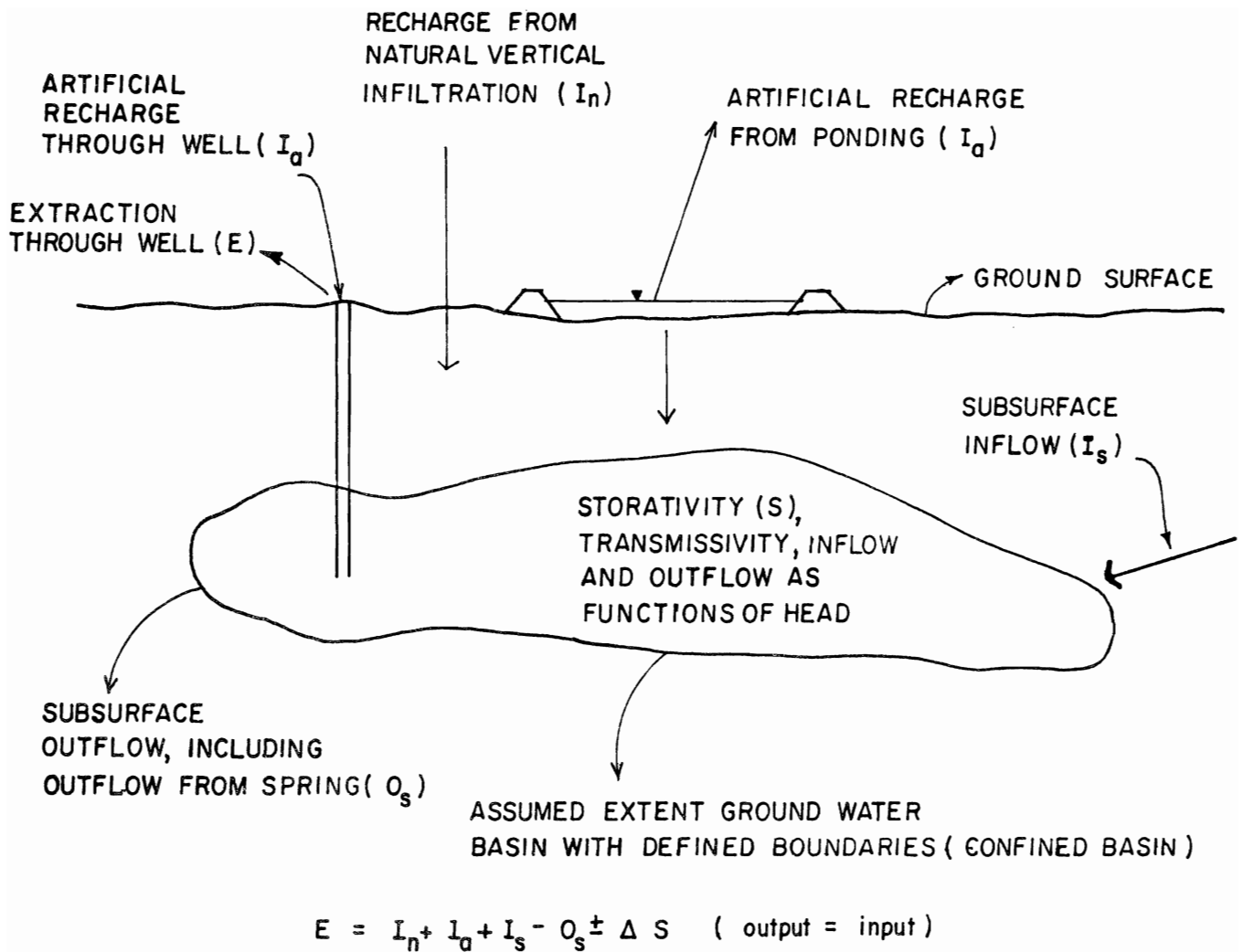


FIG. 9 : SIMULATION MODEL OF A GROUNDWATER BASIN. E (EXTRACTION) CAN BE SOLVED WHEN INFLOW AND OUTFLOW ARE KNOWN AND CAN BE ASSESSED IN TERMS OF TRANSMISSIVITY

Trial and error calculations with other combinations will show that this value cannot be exceeded. The solution found also satisfies the area and water constraints, as follows:

500 tons sugar at 0.2 acres/ton require	100 acres
125 tons cotton at 0.4 acres/ton require	50 acres
area available	<u>150</u> acres
500 tons sugar at 0.4 acre-feet/ton require	200 acre-feet
125 tons cotton at 1.6 acre-feet/ton require	<u>200</u> acre-feet
water available	400 acre-feet

Simulation modelling

There is no clear distinction between the type of modelling referred to in the preceding section and simulation modelling. However, it is convenient to refer to certain modelling under this heading in order to draw attention to some points that have so far not been covered.

Simulation modelling is well-known. It includes physical simulation modelling of river channels and estuaries and physical analogue models such as the Hele-Shaw model, used for studying flow phenomena. The latter model has been used in Israel in a study of the movement of sea water inland as a result of fresh water withdrawal or recharge close to the coast, by observing the behaviour of two fluids of different density between two parallel glass plates spaced a few millimetres apart.

Simulation modelling is now often attempted without recourse to physical modelling. Diagrams or networks are drawn for phenomena such as the behaviour of an estuary or a ground-water basin, exemplified by Figure 9 in which general factors affecting the flow pattern of a groundwater basin are presented. This diagram simulates a generally complex situation in a simple manner, on the basis of which an analysis may be attempted.

Many models of this type are over-simplified in order to (a) encompass the natural system, (b) find an explanation for its behaviour, or else (c) to optimize management. While many studies have recently been made, practical application within the field of operation and maintenance seems to be confined to the management of ground water. The usefulness of this type of modelling for ground water systems is still controversial (1).

It may be possible to assign values to inputs (natural and artificial recharge) and outputs (withdrawal by pumping or spring outflow), but reliable solutions are difficult to obtain because of a general absence of information on transmissivity within aquifers and within critical areas surrounding them. Without information on transmissivity in areas away from wells, aquifer responses are hardly assessable. Thus, in Israel, where ground-water management is at an advanced stage, field management is still based on observations of water levels within aquifers in response to recharge and withdrawal, despite the availability of results from modelling techniques (8).

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APPENDIX 1 List of computer programmes of interest to operation and maintenance of water resources projects, developed by the U.S. Bureau of Reclamation.

Budget and cash flow

- Quarterly budget report
- Year-end budget report
- General ledger summary tabulations
- Budget summary
- Cash flow report
- Outstanding accounts
- Accrued expenditure and accounts receivable

Investment status

Bond status update
Paid up bond report
Present worth values

Costing and analysis (see also under operation and maintenance, and hydropower)

Construction repayment assessment lists
Municipal and industrial repayment analysis study
Cost estimate
Bi-weekly cost estimate programme
Year-end cost summary report
Gas and oil pay out lists
Water fowl repayments

Inventory

Real property intermediate file
Real property list of change
Update real property master file
End of year real property land status
Moveable capitalized property records

Personnel

Annual personnel reports
Personnel roster
Create-update the applicant file
Detailed recruitment summary report
Update master training file
Pay-roll calculate and cost-budget account
Pay-roll master file update
Temporary appointment report

Operation and maintenance

- Machine utilization and material cost
- ADP equipment utilization (ADP - Automatic data processing)
- Job number file maintenance programme
- Determination of average service lives
- Total operation planning system
- Equipment failure report
- Irrigation maintenance update
- Motor vehicle expense report

Hydropower

- Power systems average rate, repayment studies
- Coordinated power operation studies
- Land analysis
- Summary of power sales determination
- Net revenue calculation
- Repayment program
- Transmission line performance
- Project use power computation
- Powerplant hourly load duration curves
- Powerplant generation analysis
- Power rate and repayment table
- Generator reactive capability curves
- Parallel operation of A-C and D-C transmission
- Power system short circuit
- Powerplant peak-off-peak generator
- Power billing program
- Power rate and repayment table

Irrigation and land use

- Prepare land utilization reports
- Land use and crop summary
- Farm budget calculation
- Seepage loss from small canals and laterals
- Irrigation discharge quantities
- Annual crop census
- Canal and lateral earthwork end areas
- Borrow area excavation tables
- Earthwork volume system
- Properties of soils
- Land classification
- Soil chemical analysis
- Irrigation requirements
- Consumptive use of water
- Evapotranspiration and irrigation efficiencies

Hydrology

- Computation of venturi meter discharge tables
- Radio-isotopes discharge measurements
- Water surface profiles by standard step method
- Flow net for abrupt offsets in a canal
- Venturi meter calibration
- Analysis of water hammer in pipe line systems
- Flow duration analysis of stream flow records
- Flood study hydrograph computation
- Depth-duration analysis
- Drought analysis

Ground water operation

- Ground water flow by relaxation method
- Drawdown curves with curvilinear flow
- Ground water contour plot
- Statistical analysis of piezometer data
- Ground water hydrograph plot

General

- Network analysis system
- Water supply and reservoir operation studies
- College library file update
- Forecast of water supply and requirements
- Water quality analysis
- Stochastic (probablistic) operation studies

LINCOLN PAPERS IN WATER RESOURCES

- 1 Water Resources Symposium 40th ANSAAS Congress
Proceedings - Part 1 (April 1968) - out of print
- 2 Water Resources Symposium 40th ANZAAS Congress
Proceedings - Part 2 (April 1968) - out of print
- 3 Hydrological Characteristics of Catchments -
Walter C. Boughton. Lag Time in Natural Catchments:
A.J. Askey (July 1968) - out of print
- 4 Financing Catchments Schemes in New Zealand. Papers
presented at a training course organised by the New
Zealand Association of Soil Conservation (August 1968)
- 5 The Measurement of Soil Loss from Fractional Acre
Plots: J. A. Hayward (September 1968)
- 6 Contour Plans by Computer : Walter C. Boughton
(February 1969)
- 7 The Use of Fractional Acre Plots to Predict Soil
Loss from a Mountain Catchment: J. A. Hayward
(June 1969)
- 8 Watershed Management Part 1: Editor, J. A. Hayward
(December 1969)
- 9 Watershed Management Part 2: Editor, J. A. Hayward
(December 1969)

